VRGE: An Immersive Visualization Application for the Geosciences

David A. B. Hyde[*] Tyler R. Hall[†] Jef Caers[‡]

Stanford University

ABSTRACT

The rapid onset of inexpensive, portable virtual reality (VR) devices has created opportunities for scientific visualization tools that harness this new, immersive modality. Researchers in the geological sciences, in particular those focused on earth resources (energy, water, minerals), are faced with significant challenges in building and understanding increasingly complex geological models. In this paper, we address these joint opportunities by introducing the Virtual Reality Geomodeling Environment (VRGE): a scientific visualization tool leveraging the Oculus Rift VR system, specialized for users involved in geological modeling. VRGE offers a number of features for viewing and interacting with geological models in VR, including human-centric navigation and manipulation, implicit surface editing, visual conditioning, and uncertainty analysis. Moreover, we examine how the design of VRGE meets current needs of the earth resources industry, in the context of reviewing the state-of-the-art, conducting an expert survey, and discussing performance.

Keywords: Virtual reality, scientific visualization, geological modeling, implicit surfaces

Index Terms: Human-centered computing—Scientific visualization; Computing methodologies—Virtual reality

1 INTRODUCTION

Many visualization systems aim to provide an immersive experience with natural controls for the end user [1, 4, 7, 9, 21]. Such systems include 3D desktop graphics, multi-monitor or projector-based cave automatic virtual environments (CAVEs), haptic feedback devices, and, more recently, virtual and augmented reality head-mounted displays. Devices such as the Oculus Rift and HTC Vive are affordable and relatively portable, which offer the potential for widespread adoption within an organization or industry. The use of VR in scientific visualization has been earnestly studied for the past several decades [5] and has borne applications in diverse fields such as archaeology, education, computational fluid dynamics, and medicine [30].

A particularly interesting domain where portable VR systems may provide substantial benefit is the geosciences, especially for those working with earth resources such as energy, water, or minerals. Recent developments in exploration technology as well as an explosion in computational power have given rise to large-scale (though often sparse), precise data sets that in turn have made digital modeling, analysis, understanding, and communication increasingly time-consuming and sophisticated challenges. These challenges are largely visual: properties such as size, shape, and structure of a resource deposit are often what geoscientists use to make planning decisions [2, 11].

This paper presents the Virtual Reality Geomodeling Environment (VRGE), an immersive visualization application for the geosciences. VRGE addresses the following relevant needs of those working with earth resources: 1) viewing and editing various types of geological data and models (including implicit 3D surface models); 2) understanding statistical properties such as uncertainty in a visual manner; and 3) providing a user experience that is designed to be natural and immersive. We conducted a survey of industry experts and argue how our software is useful for our intended application area. We discuss the design and implementation of VRGE's initial feature set, including special considerations for performance and VR.

The contributions of this paper include: 1) a survey dataset of industry experts, illuminating current difficulties in geomodeling and the promise of VR applied to this industry; 2) a novel application for visualizing, editing, and analyzing geological models and uncertainty in immersive virtual reality; and 3) the presentation of an immersive means of communicating uncertainty regarding 3D surfaces.

*e-mail: dabh@stanford.edu
†e-mail: trhall@stanford.edu
‡e-mail: jcaers@stanford.edu

2 BACKGROUND

2.1 Motivation

Although our methods apply to all areas of earth resources, in this work we focus on mineral resources. We conducted a survey across personal networks and LinkedIn, which yielded responses from 67 mineral resource geologists. Respondents were geographically diverse and work with a wide variety of commodities (copper, iron, gold, uranium, etc.). The survey contained a number of multiple-choice questions regarding the respondents' current workflows and their perspectives on visualization and VR, as well as a number of open-ended text questions. We highlight several questions that provided insight into the state-of-the-art of the industry as well as users' familiarity and interest in immersive visualization.

Table 1: Responses to the expert survey question, "*How experienced are you with virtual reality or augmented reality systems?*" While most respondents were aware of VR/AR, no one surveyed currently uses these technologies in their workflow.

Response	Count	Percent
Not heard of it	1	1.5%
Heard of it	*47*	*70.1%*
Used it once or twice	9	13.4%
Use it often	5	7.5%
Use it in my workflow	0	0.0%
No response	5	7.5%
Total	67	100.0%

Table 2: Responses to the expert survey question, "*Do you think immersive visualization, such as virtual reality, could be useful in your workflow?*" Results indicate potential industry users are already aware of the benefits of VR-based visualization or are at least open to incorporating such technologies if they prove useful.

Response	Count	Percent
Yes	*25*	*37.3%*
Maybe	22	32.3%
No	15	22.4%
No response	5	7.5%
Total	67	100.0%

2018 IEEE Scientific Visualization Conference (SciVis)
21-26 October 2018, Berlin, Germany
978-1-5386-6882-5/18/$31.00 ©2018 IEEE

Table 1 shows respondents' experience with VR or AR systems. 98.4% of those who provided a response reported at least basic awareness of VR or AR systems, but zero respondents reported that they use VR/AR systems at any point in their workflow. This highlights an interesting disconnect with respondents' interest and perceived utility of immersive visualization, see Table 2. 75.8% of those who provided a response believe immersive visualization could be useful in their workflow, despite no one surveyed actually using these technologies. These results alone motivate researching immersive visualization for the geosciences and an attempt to integrate them into existing workflows.

Another survey question, shown in Table 3, quantifies the sentiment that geomodeling is becoming an increasingly demanding challenge. The plurality of respondents (35.8%) stated that building their current geological model would take a single user between one week and one month, while almost as many users (34.3%) stated that the same task would take them between one and six months. This suggests the importance of technologies that can aid in the modeling process and reduce time-to-solution.

Table 3: Responses to the expert survey question, "*How long do you think it would take for a single person to reasonably rebuild your geological model, provided all current drillhole data?*" Results suggest the complexity of state-of-the-art models used in the geosciences.

Response	Count	Percent
Less than a day	4	6.0%
Less than a week	10	14.9%
Less than a month	*24*	*35.8%*
One to six months	23	34.3%
Six months to a year	5	7.5%
One to two years	0	0.0%
More than two years	1	1.5%
Total	67	100.0%

Table 4: Responses to the expert survey question, "*How easy is it to communicate geological uncertainty to mine engineers?*" A plurality of responses indicate difficulty with communicating uncertainty to mine engineers, a crucial step in the modeling workflow.

Response	Count	Percent
Easy	16	23.9%
Fair	9	13.4%
Difficult	14	20.9%
Very Difficult	*18*	*26.9%*
No Response	10	14.9%
Total	67	100%

In Table 4, we show the results obtained when asking respondents how difficult they find communicating uncertainty to mine engineers. Excluding the 10 non-responses, 43.9% of respondents suggested that it is not a significant challenge, while the majority of the respondents (56.1%) indicated difficulty, implying that there is ample room to develop more effective means of communicating uncertainty.

In addition to quantitative responses, we collected qualitative, free-form answers. For instance, when asked how VR might aid their workflow, respondents made suggestions such as: 1) using VR would be more effective for visualization or presentations (29 responses); 2) VR would simplify navigating a complex model (10 responses); 3) VR visualization could serve as a qualitative method for revising a model (11 responses). Common concerns about VR included: 1) difficulty of incorporating quantitative/statistical analysis (4 responses); potential motion sickness (2 responses); 3) learning curve/unfamiliar controls (2 responses).

Asked more generally about visualization, 38 respondents suggested the following improvements: 1) 3D monitors (15 responses); 2) additional 2D monitors (13 responses); 3) improved graphics performance (10 responses). Other responses regarding improving modelers' current workflow included making software interoperable with more open, standardized data formats (4 responses), creating more natural navigation (5 responses), and improving the model validation and reconciliation process (3 responses). Together, the results of our expert survey provide insight into users' perspectives of the state-of-the-art in geological modeling and visualization, and motivate a number of design and implementation protocols.

2.2 Related Work

2.2.1 Modeling in the Geosciences

Constructing 3D geological models from field and subsurface data is required for prediction and risk assessment in fields such as reservoir forecasting [28], mine planning [6], and groundwater assessment [14]. According to our survey, most geologists digitize models (explicitly) along section lines (41 responses), a subset of whom draw wireframe models on paper, followed by digital explicit modeling (9 responses). Explicit modeling provides fine-grained control over model details, but results in a significant time-burden. In contrast, implicit modeling techniques, such as radial basis function [31] and level set methods [8, 10], allow for multiple realizations of the same deposit to be modeled more quickly than traditional techniques. While our survey suggests implicit modeling is not as widely used (33 responses), perhaps due to its novelty, it can greatly improve geoscientists' efficiency, leading its growing popularity[1].

Earth resource models are typically built via a commercial software package. Based on our expert survey, the majority of resource geologists are using Leapfrog, Datamine, Vulcan, or MineSight to model resources (43 responses). Moreover, as of 2015 [26], there were no commercially available virtual reality systems in the mining industry using head-mounted displays (HMDs). Since then, at least two mining companies, Newmont[2] and Rio Tinto[3], have developed training and touring experiences for HMDs. However, to the authors' knowledge, no software currently exists for HMD-based interactive geomodeling (i.e. beyond static visualization) for the mining industry, nor the geosciences as a whole.

2.2.2 Visualization, Virtual Reality, and the Geosciences

Our present contribution is a scientific visualization and interactive modeling application for the geosciences, designed for use with head-mounted virtual reality displays. A number of works provide immersive visualization for the geosciences, largely focusing on CAVEs. Lidal et al. [18] present several applications for oil recovery using a CAVE. Helbig et al. [15] describe a visualization tool built on top of Paraview for exploring atmospheric data in a CAVE. Gruchalla [12] developed a CAVE-based well-path editing tool and quantifies benefits of immersion. A geoscience-focused visualization tool is presented in Billen et al. [3], though HMDs are not considered, only volumetric grid data is rendered, and no interaction (e.g. model editing) is supported. A careful review of immersive visualization in the geosciences is found in Sherman et al. [24], showing CAVEs are clearly more common than HMDs. Harrison et al. [13] present and evaluate a visualization application for analyzing the petrophysical properties of core samples, but do not consider immersive displays. Isosurfaces have been rendered in VR , and immersive environments have been shown to yield quantitative benefits in user performance

[1] See `http://www.stonechange2016.com/sites/default/files/S3.2.%20SRK%20-Advances%20in%203D%20geological%20modelling.pdf`.

[2] See `https://blog.kitware.com/kitware-and-newmont-guide-mining-with-virtual-reality/`.

[3] See `https://www.immersivetechnologies.com/news/news2017/Virtual-Reality-Training-WorksiteVR-Quest-A-Leap-Forward-in-Personnel-Induction-at-Rio-Tinto-Oyu-Tolgoi-Mine.htm`.

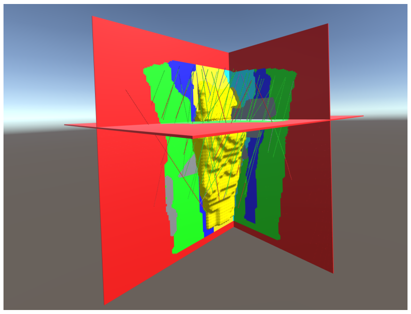

Figure 1: x-, y-, and z-axis cross-sections of 3D surface data are displayed in VRGE, along with an individual surface in yellow. Colors correspond to which of the seven surfaces in this example is present at a particular spatial location. Correspondingly-colored drillholes are also rendered, informing the user about model conditioning.

[17, 22, 29]. VRGE differentiates itself from previous systems by being primarily designed for and tested using a consumer HMD, the Oculus Rift. We also amalgamate several disparate features such as isosurface visualization, drillhole rendering and planning, and viewing volumetric grid data including cross-sections into a cohesive application. Unlike its predecessors, VRGE allows for interactive editing of 3D surfaces. In addition, we describe implementation optimizations that enable VRGE's high performance. Finally, VRGE incorporates a recent visual method for understanding uncertainty.

3 Design and Implementation

VRGE offers several core features, which are designed to address use cases suggested by respondents to our industry expert survey.

3D Surface Viewing: Earth resource models are inherently 3D. VRGE can load and display collections of both explicit and implicit 3D surfaces. Explicit models are assumed to be triangulated surfaces and can be parsed from the standard OBJ file format. Implicit surfaces are parsed from a file that stores a multidimensional array of level set values sampled on a 3D grid, and then rendered using an implicit surface shader or by finding an explicit representation of an isocontour of the level set. For sequences of surfaces, such as those that result from a physical simulation, VRGE has controls to step between frames and to play a continuous movie of evolving surfaces. When multiple surfaces are present for a single frame (as is often the case), VRGE also has controls to toggle between showing one or multiple surfaces and to iterate through the individual surfaces.

Cross-Section Viewing: Viewing cross-sections of resource deposits is a common technique used by geoscientists in order to understand the structures of and relationships between lithologies, ore types, or grade shells. As seen in Figure 1, VRGE can display one or more simultaneous cross-sections of surfaces. For implicit surfaces, cross-section colors are determined by examining level set values on the underlying grid containing the data. The same feature allows viewing arbitrary volumetric grid data supplied by the user.

Visualizing Other Geological Data: VRGE is extensible to visualizing a variety of different forms of geological data. For example, VRGE can efficiently render large point clouds, such as assay information obtained by reverse circulation or diamond core drill rigs (see Figure 1). This enables users to immersively understand how closely their surface models align with known drillhole data.

Implicit Surface Editing: In addition to viewing and analyzing models and data, VRGE contains features for real-time editing of implicit surface models (level sets). For example, VRGE has a sculpting brush that allows grabbing, pulling, and pushing sections of the surface (see Figure 2). Controls vary the radius and intensity of the brush. In practice, our implementation computes a triangulation of the implicit surface, moves vertices of that explicit representation,

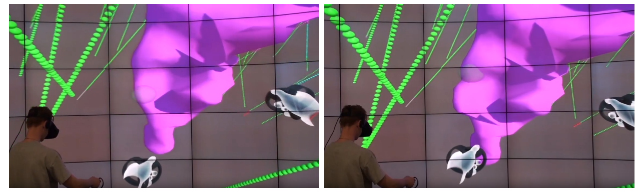

Figure 2: Using a sculpting brush (gray-green sphere) to deform an initial implicit surface (pink, left) to a desired state (right).

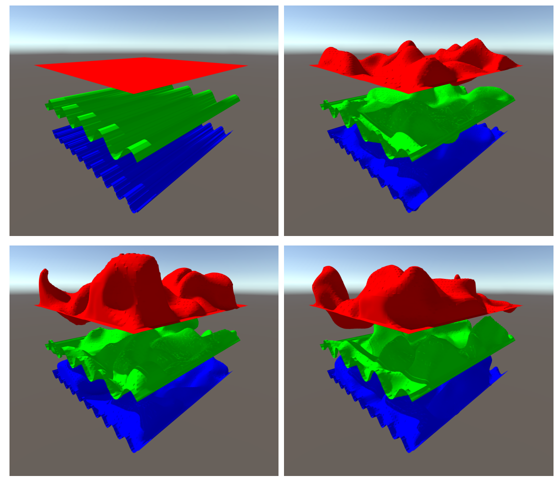

Figure 3: Surfaces evolving under the method described in Yang et al. [33]: frames 0, 25, 50, 100 (left-to-right, top-to-bottom). On the red surface, the area nearest the camera shows significant fluctuation, indicating high uncertainty. In contrast, the rear left portion of the green surface remains relatively stable, indicating greater certainty.

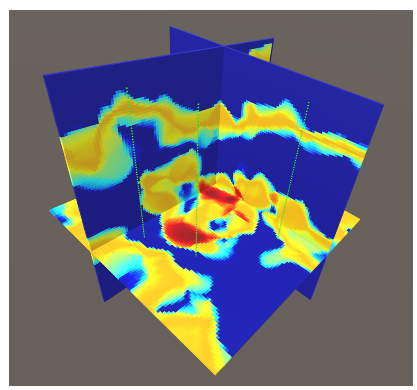

Figure 4: Entropy maps quantifying the uncertainty of the example in Figure 3. Cooler (more blue) regions, near drillholes, signify certain regions, while warmer (more red) regions indicate greater uncertainty. We take the logarithm of the normalized raw entropy values for a more dynamic color map, with the final values ranging from -1.7 (darkest blue) to $+1.3$ (darkest red). Entropy quantifies the visual understanding of uncertainty provided by "movies" such as Figure 3.

and then re-initializes a level set based on the modified surface (future work will eschew the intermediate explicit representation). While interactive level set editing is well-studied, e.g. Museth et al. [20], and implicit surfaces have been rendered in VR, e.g. Satriadi et al. [22], VRGE is to the authors' knowledge the first system that supports interactive level set editing in immersive VR.

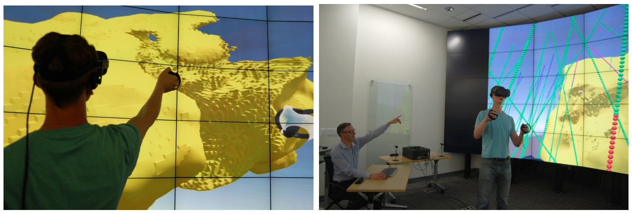

Figure 5: (Left) A user grabs and rotates a surface by squeezing and holding a trigger on one of the Touch controllers. The Touch avatars aid with immersion by providing realistic representations of hands, including detection of gestures such as pointing, pushing buttons, or making a fist. (Right) A user navigates the environment in VR, while a colleague can manipulate the view using a mouse and keyboard. VRGE supports multiple simultaneous VR and desktop users.

Visualizing 3D Surface Uncertainty: Assessing risk due to subsurface uncertainty is one of the main challenges the earth resource industry faces in terms of economically viable production and extraction [23], due to the computational inefficiency of manual or Monte Carlo-based approaches as well as the inability of certain techniques to support models with uncertain topology, not only geometry [25]. In the recent work of Yang et al. [33], uncertainty of complex geological surfaces is represented using a "movie." Instead of Monte Carlo, Yang et al. [33] generates a Markov chain of 3D surface realizations by iteratively applying a stochastic velocity field to level set surfaces. This process produces smooth "movement" at areas distant from control points (e.g. drillholes). Thus, uncertainty is directly tied to surface movement. We integrated this method into VRGE, thus enabling users to immersively understand uncertainty associated with their 3D surface models by studying which portions of the surfaces move substantially or remain relatively stationary. This aims to improve communication of geological uncertainty to stakeholders who may not be familiar with the topic. Figure 3 shows the movie of three synthetic models over 100 iterations. Three drillholes constrain certain areas of the models, while uncertain parts of the model freely move under the stochastic velocity field.

Human-Centered Controls: VRGE is designed as a VR-first application, though it also runs in a traditional desktop environment with keyboard and mouse. In VR, we aim to make controls intuitive for the end-user in order to lower the learning curve as well as increase presence and immersion. For example, rotating one's head while wearing the VR headset rotates the camera's view. Walking in physical space pans the camera. One Touch controller is used per hand. A joystick on the dominant hand controller pans the view at an accelerated speed. Symmetrically-positioned buttons on the two Touch controllers provide opposite functionality; e.g. the lowest button on the dominant hand advances a movie by one frame, while the lowest button on the non-dominant hand rewinds by one frame. Additionally, triggers on the controllers allow for grabbing, moving, and rotating surfaces, which allows a user to closely and carefully inspect a model without moving. Figure 5 shows a user "holding" a surface in one hand while rotating the surface by rotating their arm.

Immersive Collaboration: Collaboration is a grand challenge of visualization [16, 27]. In application areas of scientific visualization such as earth resources, collaboration is particularly important, as the model of a resource deposit may be used by a number of stakeholders in the decision-making process [19]. VRGE offers the capability to be displayed simultaneously in HMD and desktop environments (see Figure 5 Right), which allows for users to be present in virtual space while others interact with the model outside of VR. Additionally, VRGE supports multiple HMD users, where each user can assume a digital avatar and simultaneously interact with the same model. This offers a large advantage over multi-monitor or CAVE environments, which are not viable options for large groups of simultaneous users.

3.1 Implementation and Performance

VRGE is written in C# and is based on the Unity game engine. A major benefit of Unity is cross-platform compatibility; we anticipate adapting our code to additional mixed reality platforms in future work. VRGE is designed for real-time interaction, which is key for creating immersion and presence in VR [5, 32]. To that end, I/O performance for large data sets is a key concern. When data is loaded, VRGE creates cached copies of the data on disk in custom binary formats that align with Unity's internal data structures. Binary (de)serialization is highly efficient, primarily only limited by disk performance. VRGE also opportunistically caches data in memory when free memory is available, in order to minimize the number of loads and saves from disk. For sequences of data, VRGE can also prefetch data from disk before a user starts interacting with later frames. Our test system used an Nvidia GTX 1070 Ti GPU, a 7200RPM hard drive, a recent Intel i5 CPU, and Windows 10.

Our experiments included a test scene with three synthetic surfaces simulated over 100 frames (700MB total), and a real-world mineral dataset of seven mineral surfaces composing a porphyry copper deposit, also simulated over 100 frames (10GB total). The implicit surfaces are sampled on a uniform Cartesian grid of resolution 100^3 for the synthetic data and $198 \times 228 \times 237$ for the copper data. When interacting with either dataset, VRGE comfortably exceeds the 90 fps recommended to achieve comfortable experiences in VR with the Oculus Rift[4]. This was greatly aided by optimizing the rendering of volumetric grid data for cross-sections. For instance, in the case study shown in Figure 1, 146,106 cubes are rendered to represent the level set sample values. We took advantage of the GPU batch instancing API provided by Unity, combined with a parameterized HLSL surface shader, in order to minimize the number of GPU draw calls required to render these objects and in turn maximize the framerate. The shader source code is lightly modified from Unity's GPU Instancing guide[5]. In Figure 1, no more than 595 batch draw calls per frame were observed, saving up to almost 300,000 draw calls per frame over individual draw calls for each cube. As we tested our software on real-world data sets, we are confident in the performance of our implementation for comfortable, practical use.

4 Conclusions

We have introduced VRGE, an interactive geoscientific visualization application developed specifically for immersive VR. An expert survey illuminated various challenges in the modeling workflow for earth resources, indicating need for: 1) an immersive visualization tool; 2) reduction of lag time between data collection and interpretation; and 3) improved communication of geoscientific data to decision-makers. VRGE addresses these needs via an efficient implementation of a core feature set that includes explicit and implicit surface viewing, volumetric grid data and cross-section viewing, interactive implicit surface editing, visualization and quantification of 3D surface uncertainty. VRGE offers simultaneous, collaborative immersion for any number of researchers using commodity VR headsets, alleviating cost and portability limitations that hinder the accessibility and adoption of CAVE and multi-monitor display modalities. In the future, we will incorporate diegetic UI elements[6] into VRGE, e.g. displaying statistical quantities beside surfaces. Finally, we plan to design and test collaborative experiences in VRGE, and to conduct a formal, large-scale user study of our application.

Acknowledgments

This research was supported by a grant from BHP.

[4]See `https://support.oculus.com/guides/rift/latest/concepts/book-rug/`.

[5]See `https://docs.unity3d.com/Manual/GPUInstancing.html`.

[6]See `https://unity3d.com/learn/tutorials/topics/virtual-reality/user-interfaces-vr`.

References

[1] C. Anthes, R. J. García-Hernández, M. Wiedemann, and D. Kranzlmüller. State of the art of virtual reality technology. In *2016 IEEE Aerospace Conference*, pp. 1–19. IEEE, 2016. doi: 10.1109/AERO.2016.7500674

[2] R. C. Berg, S. J. Mathers, H. Kessler, and D. A. Keefer. Synopsis of current three-dimensional geological mapping and modeling in geological survey organizations. *Illinois State Geological Survey Circular*, 578, 2011.

[3] M. I. Billen, O. Kreylos, B. Hamann, M. A. Jadamec, L. H. Kellogg, O. Staadt, and D. Y. Sumner. A geoscience perspective on immersive 3D gridded data visualization. *Computers & Geosciences*, 34(9):1056 – 1072, 2008. doi: 10.1016/j.cageo.2007.11.009

[4] F. P. Brooks. What's real about virtual reality? *IEEE Comput. Graph. Appl.*, 19(6):16–27, Nov. 1999. doi: 10.1109/38.799723

[5] S. Bryson. Virtual reality in scientific visualization. *Commun. ACM*, 39(5):62–71, May 1996. doi: 10.1145/229459.229467

[6] E. Cowan, R. Beatson, H. Ross, W. Fright, T. McLennan, T. Evans, J. Carr, R. Lane, D. Bright, A. Gillman, P. Oshust, and M. Titley. Practical implicit geological modelling. In *5th International Mining Geology Conference*. The Australian Institute of Mining and Metallurgy, Bendigo, Victoria, November 2003.

[7] C. Cruz-Neira, D. J. Sandin, and T. A. DeFanti. Surround-screen projection-based virtual reality: The design and implementation of the CAVE. In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '93, pp. 135–142. ACM, New York, NY, USA, 1993. doi: 10.1145/166117.166134

[8] R. Fedkiw and S. Osher. *Level set methods and dynamic implicit surfaces*. 2002.

[9] P. Fite-Georgel. Is there a reality in industrial augmented reality? In *2011 10th IEEE International Symposium on Mixed and Augmented Reality*, pp. 201–210, Oct 2011. doi: 10.1109/ISMAR.2011.6092387

[10] F. Gibou, R. Fedkiw, and S. Osher. A review of level-set methods and some recent applications. *Journal of Computational Physics*, 353:82–109, 2018. doi: 10.1016/j.jcp.2017.10.006

[11] P. Glynn, L. Jacobsen, G. Phelps, G. Bawden, V. Grauch, R. Orndorff, R. Winston, M. Fienen, V. Cross, and J. Bratton. 3D/4D modeling, visualization and information frameworks: current US Geological Survey practice and needs. In *Three-Dimensional Geological Mapping*, pp. 33–38. Geological Survey of Canada, 2011. doi: 10.4095/289609

[12] K. Gruchalla. Immersive well-path editing: investigating the added value of immersion. In *IEEE Virtual Reality 2004*, pp. 157–164, March 2004. doi: 10.1109/VR.2004.1310069

[13] D. G. Harrison, N. D. Efford, Q. J. Fisher, and R. A. Ruddle. PETMiner - a visual analysis tool for petrophysical properties of core sample data. *IEEE Transactions on Visualization and Computer Graphics*, 2018. doi: 10.1109/TVCG.2017.2682865

[14] I. Hassen, H. Gibson, F. Hamzaoui-Azaza, F. Negro, K. Rachid, and R. Bouhlila. 3D geological modeling of the Kasserine Aquifer System, Central Tunisia: New insights into aquifer-geometry and interconnections for a better assessment of groundwater resources. *Journal of Hydrology*, 539:223 – 236, 2016. doi: 10.1016/j.jhydrol.2016.05.034

[15] C. Helbig, H.-S. Bauer, K. Rink, V. Wulfmeyer, M. Frank, and O. Kolditz. Concept and workflow for 3D visualization of atmospheric data in a virtual reality environment for analytical approaches. *Environmental Earth Sciences*, 72(10):3767–3780, Nov 2014. doi: 10.1007/s12665-014-3136-6

[16] P. Isenberg, N. Elmqvist, J. Scholtz, D. Cernea, K.-L. Ma, and H. Hagen. Collaborative visualization: Definition, challenges, and research agenda. *Information Visualization*, 10(4):310–326, 2011. doi: 10.1177/1473871611412817

[17] B. Laha, D. A. Bowman, and J. J. Socha. Effects of VR system fidelity on analyzing isosurface visualization of volume datasets. *IEEE Transactions on Visualization and Computer Graphics*, 20(4):513–522, April 2014. doi: 10.1109/TVCG.2014.20

[18] E. M. Lidal, T. Langeland, C. Giertsen, J. Grimsgaard, and R. Helland. A decade of increased oil recovery in virtual reality. *IEEE Computer Graphics and Applications*, 27(6):94–97, Nov 2007. doi: 10.1109/MCG.2007.141

[19] C.-R. Lin, R. B. Loffin, and T. Stark. Virtual reality for geosciences visualization. In *Proceedings. 3rd Asia Pacific Computer Human Interaction (Cat. No.98EX110)*, pp. 196–201, Jul 1998. doi: 10.1109/APCHI.1998.704208

[20] K. Museth, D. E. Breen, R. T. Whitaker, S. Mauch, and D. Johnson. Algorithms for interactive editing of level set models. In *Computer Graphics Forum*, vol. 24, pp. 821–841. Wiley Online Library, 2005. doi: 10.1111/j.1467-8659.2005.00904.x

[21] T. Ni, G. S. Schmidt, O. G. Staadt, M. A. Livingston, R. Ball, and R. May. A survey of large high-resolution display technologies, techniques, and applications. In *IEEE Virtual Reality Conference (VR 2006)*, pp. 223–236, March 2006. doi: 10.1109/VR.2006.20

[22] K. A. Satriadi, K. Stephens, C. Atkinson, M. Cordeil, and T. Czauderna. Immersive isosurface visualisation for engineering datasets. In *2017 International Symposium on Big Data Visual Analytics (BDVA)*, pp. 1–8, Nov 2017. doi: 10.1109/BDVA.2017.8114624

[23] C. Scheidt, L. Li, and J. Caers. *Quantifying Uncertainty in Subsurface systems*. 12 2017.

[24] W. Sherman, G. Kinsland, C. Borst, E. Whiting, J. Schulze, P. Weber, A. Lin, A. Chaudhary, S. Su, and D. Coming. Immersive visualization for the geological sciences. In *Human Factors and Ergonomics*, pp. 1231–1264. 2014.

[25] R. Steele and K. Stephan. Geological weaknesses in geomodelling. In *Recognising the Limits of Reservoir Modelling - and how to overcome them*, p. 11. Petroleum Group of the Geological Society of London, 2015.

[26] P. Stothard, A. Squelch, R. Stone, E. van Wyk, M. Kizil, D. Schofield, and K. Fowle. Taxonomy of interactive computer-based visualisation systems and content for the mining industry part 2. *Mining Technology*, 124(2):83–96, 2015. doi: 10.1179/1743286315Y.0000000006

[27] J. J. Thomas and K. A. Cook. *Illuminating the Path: The Research and Development Agenda for Visual Analytics*. IEEE Computer Society, 2005.

[28] P. Thore, A. Shtuka, M. Lecour, T. AitEttajer, and R. Cognot. Structural uncertainties: Determination, management, and applications. *Geophysics*, 67(3):840 – 852, 2002. doi: 10.1190/1.1484528

[29] W. Usher, P. Klacansky, F. Federer, P. T. Bremer, A. Knoll, J. Yarch, A. Angelucci, and V. Pascucci. A virtual reality visualization tool for neuron tracing. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):994–1003, Jan 2018. doi: 10.1109/TVCG.2017.2744079

[30] A. van Dam, A. S. Forsberg, D. H. Laidlaw, J. J. LaViola, and R. M. Simpson. Immersive VR for scientific visualization: a progress report. *IEEE Computer Graphics and Applications*, 20(6):26–52, Nov 2000. doi: 10.1109/38.888006

[31] M. T. Vu. Applications of the level set method in hydro-geology. 2012. Thèse de doctorat dirigée par Adler, Pierre Michel Géologie appliquée Paris 6 2012.

[32] M. M. Wloka. Lag in multiprocessor virtual reality. *Presence: Teleoper. Virtual Environ.*, 4(1):50–63, Jan. 1995. doi: 10.1162/pres.1995.4.1.50

[33] L. Yang, D. Hyde, O. Grujic, C. Scheidt, and J. Caers. Assessing and visualizing uncertainty of 3D geological surfaces using level sets with stochastic motion (in review). *Computers & Geosciences*, 2018.